

General Biped Motion and Balance of a Human Model

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ABSTRACT

We propose an algorithm of predicting dynamic biped motions of SantosTM human model. An alternative and efficient formulation of the Zero-Moment Point (ZMP) for dynamic balance and the approximated ground reaction forces/moments are derived from the resultant reaction loads, which includes the gravity, the externally applied loads, and the inertia. The optimization problem is formulated to address the redundancy of the human task, where the general biped and the task-specific constraints are imposed depending on the task requirements. The proposed method is fully predictive and generates physically feasible human-like motions from scratch without any input reference from motion capture or animation. The resulting generated motions demonstrate how a human reacts effectively to different external load conditions in performing a given task by showing realistic features of cause and effect. **Key words:** human motion generation, Lagrangian dynamics, optimization, Zero-Moment Point.

INTRODUCTION

Predicting human motions in a physics-based simulation environment has several useful applications in the field of digital human technologies, where the dynamic models developed for human motion enhances the reality and provides physically consistent motion results and feedback. It is used to analyze and improve human motion and performance. Applications of the physics-based human motion prediction can be found in biomechanics, human task design, virtual prototyping of human-machine interaction environment, injury prediction, and sports analysis. At the same time, the simulation results provide scientific insight on the nature of human motion.

As one of the most fundamental and critical concepts to be considered in predicting the whole-body biped motion, the dynamic balance is the basic requirement that has to be strictly satisfied for physical consistency. For this reason, the dynamic balance of a biped system has been

treated by a large number of authors in various approaches. The most widely accepted criteria for dynamic balance is probably the Zero-Moment Point, or ZMP, which was first introduced in late 1960s (Vukobratović and Borovac, 2004). The ZMP has been defined as the point on the ground at which the net moment of the inertial forces and the gravity forces has no component along the horizontal axes, although several different interpretations have also been addressed. The necessary and sufficient condition for dynamic balance of biped motion is that the ZMP should be located within the foot support region (convex hull formed by the contacting feet surface), excluding the boundaries. If the ZMP is moved to the boundary of the support region, the whole mechanism starts tipping over, i.e., falling. Since then, many authors have refined and extended the concept of the ZMP or have invented other balancing criteria. Examples are the Foot-Rotation Indicator (FRI) point (Goswami, 1999), center of pressure (COP) (Sardain and Bessonnet, 2004), centroidal moment pivot (CMP) (Popovic et al., 2005), Dynamically Complementary Zero-Moment Point (DCZMP) (Takubo et al., 2005) generalized ZMP (GZMP) (Harada et al., 2006), etc.

The ZMP and other ground reference points have been used as the balancing criteria mainly for the gait synthesis and control of human models (e.g., Nagasaka et al., 2004; Xiang et al., 2007; Hirose and Ogawa, 2007). On the other hand, since the application of human motion is not limited to locomotion, some authors have modeled dynamically balanced general manipulations of biped mechanisms (Kuffner et al., 2002; Inoue et al., 2002; Park et al., 2007). Evidently, the balance and the motion generation of human model for manipulation are mainly associated with control systems where the input reference is required. The input reference motions are usually obtained from animation or motion capture experimental data (Ude et al., 2000; Pollard et al., 2002; Nakaoka et al., 2005).

In this presentation, we propose a formulation of generating dynamic whole-body biped motions and the required joint actuator torques (and forces) of a human

model using optimization. This is an extension of our previous study (Kim et al., 2006; Kim et al., 2007) using an upper-body human model. The additional modeling of the lower extremities raises several critical dynamic aspects of biped motion—the global degrees of freedom (DOFs), the balance, and the ground reaction forces and moments (GRFs). Our methodology is fully predictive, and the physically feasible motions are generated from scratch; no information on the pre-synthesized input reference is required. This is beneficial especially when the motion capture experiment is difficult due to physical or environmental limitations, or when the animation is not available from intuition. An alternative and efficient formulation of the ZMP will be introduced that incorporates all possible loads applied to the mechanism—gravity, externally applied forces and moments, and inertia. Also, the approximate GRFs will be predicted. This is in contrast to the common practical approach of calculating the ZMP from the measured data of the ground reaction forces, which again shows the fully predictive nature of our method. The general external loads are implemented through the equations of motion so that the results demonstrate effective human motions to execute a given task and show realistic features of cause and effect. Some simple manual task examples will be tested using a 3-D human model.

KINEMATIC AND DYNAMIC MODELING

The human body is a typical example of tree-structured systems with multiple limbs. The 55-DOF Santos™ whole-body human model (Xiang et al., 2007) includes the six global DOFs from a global origin as well as the lower/upper limbs, the torso, and the head (Figure 1). The pelvis is chosen as the base link for the global DOFs under rigid-body assumption. The configuration of the human open-loop kinematic chains is described by the Denavit-Hartenberg (DH) notation (Denavit and Hartenberg, 1955). The 55×1 joint variables $\mathbf{q} = [q_1^{(p)} q_2^{(p)} q_3^{(p)} q_4^{(p)} q_5^{(p)} q_6^{(p)} q_1^{(r)} \dots q_{49}^{(r)}]^T$ uniquely determines the configuration of the system.

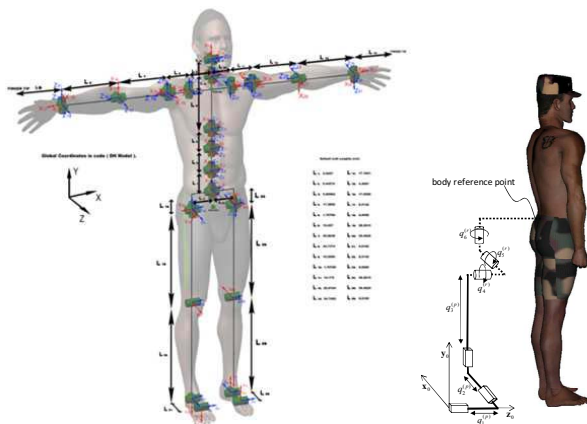


Figure 1. Santos™ human model and global DOFs.

The global motion (translations and rotations) of the body reference point located at the center of the human pelvis can also be described using the DH method with mass-free link-joint structure representing the global DOFs.

The displacements of the first three prismatic (p) joints describe the global translations of the pelvis in the 3-D xyz Cartesian coordinates (units in meters). The last three revolute (r) joint variables represent the global orientations of the pelvis in terms of Euler angles (units in radians) in a 3-D space. The global-DOF generalized coordinates are expressed as follows:

$$[q_1^{(p)} q_2^{(p)} q_3^{(p)} q_4^{(r)} q_5^{(r)} q_6^{(r)}]^T = [z_0 \ x_0 \ y_0 \ \alpha \ \beta \ \gamma]^T,$$

where α , β , and γ are the Euler angles of Z-X-Y type.

Let us consider the case where a general form of external loads $[\mathbf{F}_k^T \ \mathbf{M}_k^T]^T$ is applied to the point at ${}^k\mathbf{r}_k$ location of link k , where $[\mathbf{F}_k^T \ \mathbf{M}_k^T]^T$ is a 6×1 vector comprised of a 3×1 force vector $\mathbf{F}_k$ and a 3×1 moment vector $\mathbf{M}_k$, and ${}^k\mathbf{r}_k$ is a 4×1 position vector expressed in terms of $\{k\}$ local coordinate frame attached to link k . The equation of motion for a general open-loop kinematic chain with several general external loads is derived as follows (Kim et al., 2006).

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q}, \dot{\mathbf{q}}) + \sum_i \mathbf{J}_i^T m_i \mathbf{g} + \sum_k \mathbf{J}_k^T \begin{bmatrix} -\mathbf{F}_k \\ -\mathbf{M}_k \end{bmatrix} + \mathbf{T}(\mathbf{q}, \dot{\mathbf{q}}) \quad (1)$$

where $\boldsymbol{\tau} = [\tau_1, \tau_2, \dots, \tau_n]^T$ is the actuator torque vector, $\mathbf{M}(\mathbf{q})$ is the mass-inertia symmetric matrix, $\mathbf{V}(\mathbf{q}, \dot{\mathbf{q}})$ is the Coriolis and centrifugal force vector, $\sum_i \mathbf{J}_i^T m_i \mathbf{g}$ is the joint torque vector due to gravity, $\mathbf{J}_i$ is the Jacobian matrix of the position vector for the center of mass of i^{th} link, and $\mathbf{J}_k$ is the augmented Jacobian matrix of the position vector ${}^k\mathbf{r}_k$ with respect to $\{k\}$ local coordinate frame. The vector $\mathbf{T}(\mathbf{q}, \dot{\mathbf{q}})$ is the torque vector due to the joint stiffness and the dissipative forces such as viscous damping and Coulomb friction. The equations of motion are used to calculate the actuator torques and the global-DOF generalized torques (and forces), which are then used for various dynamics formulation such as the energy cost function, the torque constraint, and the ZMP. For actual implementation, the equations of motion (1) are reformulated into a backward recursive form for increased computational efficiency (Hollerbach, 1980; Toogood, 1989).

ZMP AND GRFS

In this section, an alternative and efficient formulation of ZMP and the approximated GRFs for a biped human model in DH representation is introduced. This is a generalization of the authors' previous work (Xiang et al., 2007).

RESULTANT REACTION LOADS

For biped motions in the real world, all the loads applied to the mechanism are reacted by the ground. Practically,

these GRFs are measured to calculate the ZMP. However, in a simulation environment where the GRFs cannot be measured directly, the ZMP should be calculated from the applied loads. The usual calculation of the ZMP thus requires heavy computation of the loads and inertias at each link. This subsection introduces an efficient formulation of the resultant reaction loads, which includes the gravity, the externally applied loads, and the inertia (including the rate of change of angular momentum). The Lagrange's equation, which is derived for the whole mechanism including the global DOFs, yields the global-DOF generalized torques as well as the mechanism's joint actuator torques without the GRFs application (Figure 2). Then the resultant reaction loads applied at the body reference point can be derived from the global-DOF generalized torques. It will be shown later that the GRFs derived from the resultant reaction loads are applied to the mechanism in the current configuration to naturally remove the global-DOF generalized torques, which ensures physical consistency.

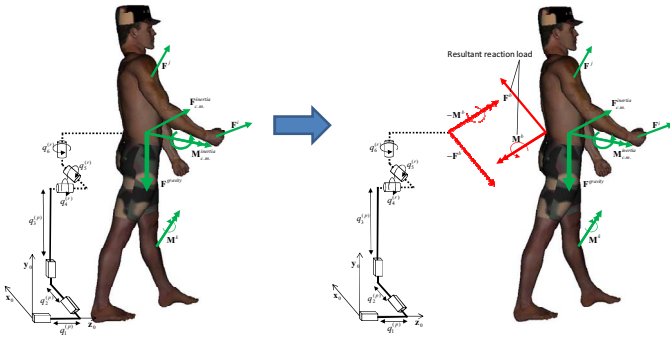


Figure 2. Free-body diagram of the human mechanism and the resultant reaction loads without GRFs.

Since the origins of the last three local frames for the global rotations are collocated with the body reference point, the 6×6 Jacobian matrix $\mathbf{J}$ of the body reference point with respect to the global-DOF generalized coordinates is a block diagonal matrix.

$$\mathbf{J} = \begin{bmatrix} \mathbf{z}_0 & \mathbf{z}_1 & \mathbf{z}_2 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{z}_3 & \mathbf{z}_4 & \mathbf{z}_5 \end{bmatrix}, \quad (2)$$

where $\mathbf{z}_i = {}^0\mathbf{z}_i$ ($i = 0, 1, \dots, 5$) is the 3×1 $\mathbf{z}$ axis vector of the i^{th} local frame expressed in terms of the global frame, and $\mathbf{0}$ is the 3×1 zero vector.

From the virtual work principle, the global-DOF generalized torques can be expressed using the Jacobian matrix and the resultant reaction loads at the body reference point, where the Jacobian matrix is partitioned into 3×3 blocks as follows.

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_1^{(p)} \\ \tau_2^{(p)} \\ \tau_3^{(p)} \\ \tau_4^{(r)} \\ \tau_5^{(r)} \\ \tau_6^{(r)} \end{bmatrix} = \mathbf{J}^T \begin{bmatrix} f_x \\ f_y \\ f_z \\ m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \mathbf{z}_0^T \\ \mathbf{z}_1^T \\ \mathbf{z}_2^T \end{bmatrix}_{(3 \times 3)} & \mathbf{F}^b \\ \begin{bmatrix} \mathbf{z}_3^T \\ \mathbf{z}_4^T \\ \mathbf{z}_5^T \end{bmatrix}_{(3 \times 3)} & \mathbf{M}^b \end{bmatrix}_{(6 \times 1)} \quad (3)$$

$[\mathbf{F}^b \ \mathbf{M}^b]^T$ is the resultant reaction loads vector applied at the body reference point of the pelvis. These resultant reaction loads are exerted by the global-DOF generalized torques.

Because of the block diagonal form of the Jacobian matrix, the effects of the resultant reaction forces and moments are decoupled, and the global translational forces and the global rotational moments can be handled separately. Since the DH structures of the global positions and orientations are identical, the common form of the Jacobian matrix and the global-DOF generalized torques can be derived. Let $[A_x \ A_y \ A_z]^T$ be the Cartesian vector of a resultant reaction loads (either a force or a moment) exerted by the global-DOF generalized torques $[a_1 \ a_2 \ a_3]^T$. Consider a sequence of coordinate frames (Figure 3) where α , β , and γ are the Euler angles described previously. From Equation (3) we have

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \tilde{\mathbf{J}}^T \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}. \quad (4)$$

The 3×3 Jacobian matrix $\tilde{\mathbf{J}}$ is

$$\tilde{\mathbf{J}} = [\mathbf{z}_{(i)} \ \mathbf{z}_{(i+1)} \ \mathbf{z}_{(i+2)}] = \begin{bmatrix} 0 & C\alpha & -S\alpha C\beta \\ 0 & S\alpha & C\alpha C\beta \\ 1 & 0 & S\beta \end{bmatrix} = \begin{bmatrix} 0 & l_2 & l_3 \\ 0 & m_2 & m_3 \\ 1 & 0 & n_3 \end{bmatrix}, \quad (5)$$

where l_{k+1} , m_{k+1} , and n_{k+1} ($k = 0, 1, 2$) represent the direction cosines of the corresponding $\mathbf{z}$ local axis with respect to the global frame. The proposed global DOFs are modeled such that the adjacent $\mathbf{z}$ vectors are orthogonal where $l_1 = m_1 = 0$, $n_1 = 1$, and $n_2 = 0$.

$$\mathbf{z}_{(i+k)} = [l_{k+1} \ m_{k+1} \ n_{k+1}]^T; \ l_{k+1}^2 + m_{k+1}^2 + n_{k+1}^2 = 1; \\ l_{k+1}l_{k+2} + m_{k+1}m_{k+2} + n_{k+1}n_{k+2} = 0 \ (k = 0, 1, 2) \quad (6)$$